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MODELLING OF THE RESPONSE OF PINE LAKE TO REDUCED INTERNAL AND EXTERNAL LOADINGS

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EXECUTIVE SUMMARY

The Pine Lake Restoration Society began various projects in 1995 designed to reduce nutrient loading and thereby control algal blooms in Pine Lake. Measures to control both external (e.g., runoff from agricultural sites) and internal phosphorus loadings (e.g., sewage in ground water and sediment phosphorus release) are being implemented. To assess the potential benefits of these projects, a water quality model (Bathtub 5.3)(Walker 1986) was used by Water Sciences Branch, Alberta Environmental Protection to predict theoretical changes in phosphorus concentration in Pine Lake after various levels of reduction in external and internal phosphorus loading. Predictive equations for Pine Lake were then developed to predict changes in algal biomass (chlorophyll *a*) and transparency (Secchi depth) based on the new phosphorus concentrations predicted by the model.

A range of reduced phosphorus loadings was modelled in four scenarios (Runs 4 to 7). Large reductions in algal biomass were predicted in each scenario. Results of Run 4 indicate that reducing internal phosphorus loading by only 25%, and reducing stream loadings to those typical of a stream in the Pine Lake basin least impacted by human activities (stream 7), would produce a 55% reduction in algal biomass. With greatly reduced loadings (Runs 6 and 7) lake algal productivity would be reduced to levels near the border between mesotrophic and eutrophic conditions. It is not possible to accurately predict changes in external and internal phosphorus loading that will occur in response to the various measures implemented by the Pine Lake Restoration Society. However, this exercise suggests that if loadings are reduced to the extent assumed in these modelling scenarios, visible improvements in water quality should occur.

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1.0 INTRODUCTION

The Pine Lake Restoration Society began various projects designed to reduce phosphorus loading from critical areas in the watershed in 1995. An application to install a hypolimnetic withdrawal system to reduce internal phosphorus loading from the sediments of Pine Lake was filed with Alberta Environmental Protection in the winter of 1996. This report presents the final results of a modelling exercise designed to determine the probable impact on lake productivity of the proposed work at Pine Lake.

Bathtub 5.3 (March 1995 release), a eutrophication model developed for the United States Army Corps of Engineers (Walker 1986), was calibrated using the 1992 data set from Pine Lake (Sosiak and Trew 1996). The 1992 calibration was verified using the 1989 data set from Pine Lake, and then run under various scenarios for reduced internal and external phosphorus loadings. Because the chlorophyll *a* and Secchi depth models in Bathtub performed poorly during the verification runs, predictive equations for these variables were developed from Pine Lake data and used in the analysis.

2.0 METHODS

2.1 MODEL CALIBRATION

Pine Lake was segmented according to the three segment boundaries historically used in water quality sampling (Figure 1). Basin morphometry and mean open-water chemistry for each segment were used. Mixed layer and hypolimnetic depth were calculated as specified in Walker (1986). Measured 1992 flow and chemistry for the tributaries of each segment were used in the calibration. Nutrient loadings from diffuse runoff were calculated as the average for gauged tributaries in each segment basin. Median precipitation chemistry and Secchi depth measured at Pine Lake in 1992 were used rather than mean values, as specified for the model, because the data were highly skewed and mean values resulted in an over-estimation of these variables. The internal phosphorus loading rate in Bathtub 5.3 was adjusted until the predicted internal load (1229 kg total phosphorus) in Run 1 matched the net internal load estimated for the open-water season in 1992 (1228 kg).

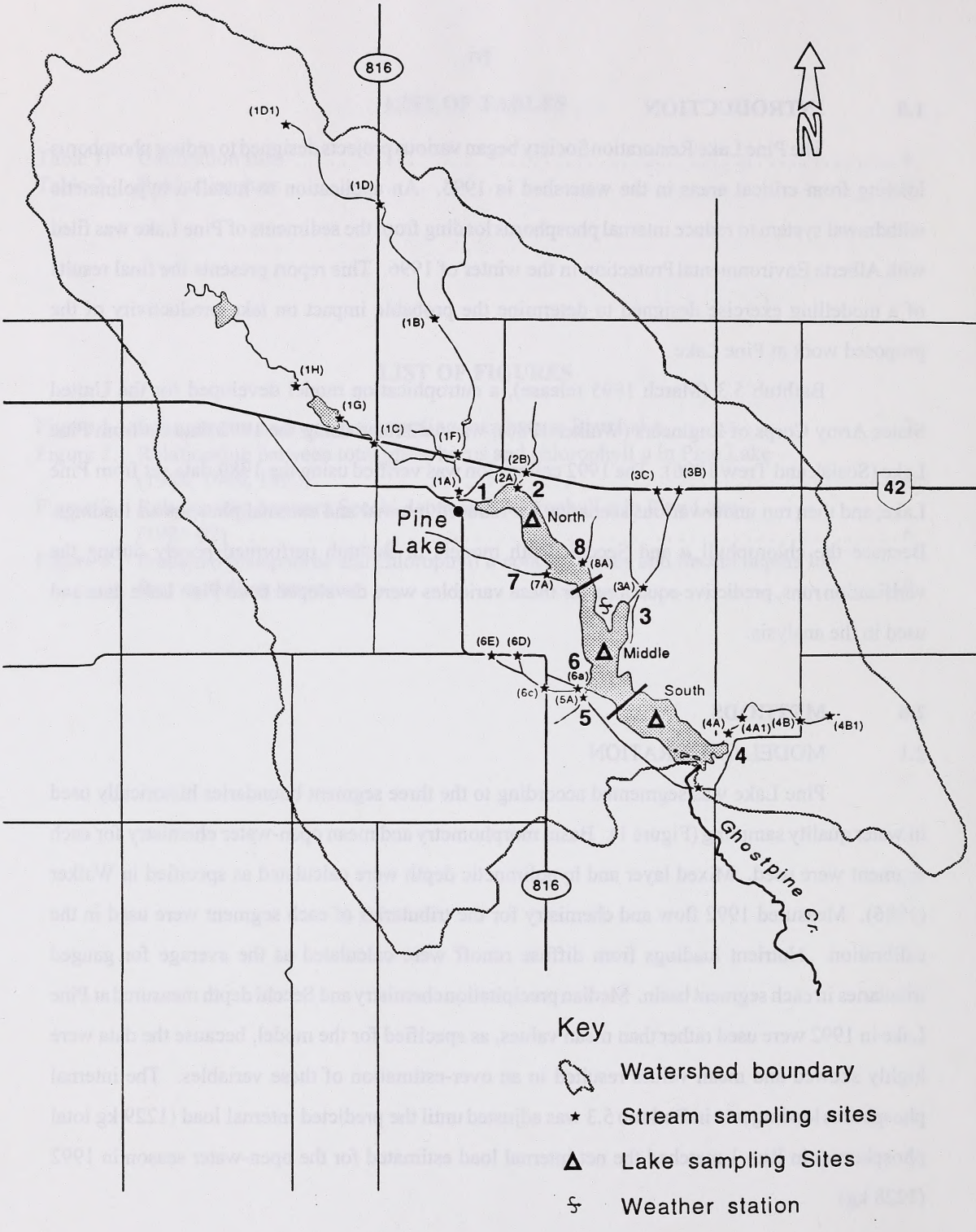

Figure 1. Lake, stream and weather sampling locations at Pine Lake.

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Annual averaging of water and mass balance calculations was employed as recommended in the draft manual for Bathtub 5.3, because of the relatively long nutrient residence time in Pine Lake. The 1992 calibration appeared to be relatively insensitive to averaging period. A series of runs with averaging over the open-water season (April 15-November 15), produced predictions that were similar to those obtained from annual averaging. The best agreement between observed and predicted data, Run 1 (Table 1) was obtained using the following predictive models in Bathtub 5.3:

MODEL TYPE	OPTION	MODEL NAME
Phosphorus balance	6.	First Order
Nitrogen balance	5.	Bachman, flushing
Chlorophyll *a*	3.	P, N; low turbidity
Secchi depth	1.	Chl *a* & turbidity
Dispersion	2.	Constant-numeric
P & N calibration	1.	Decay rates
Mass-balance tables	1.	Estimated concentrations

Minor adjustments were made to the model calibration factors for each model until model predictions matched the observed data closely (Table 1).

2.2 MODEL VERIFICATION

Model verification involves testing of the calibrated model with an independent data set derived from a different monitoring period. The 1992 calibration, with model options and calibration factors held constant was first run (Run 2, Table 1) with 1989 lake chemistry and measured tributary loadings and flow rates. The internal loading rate in 1989 appears to have been lower than in 1992, since euphotic total phosphorus levels declined over the season, instead of increasing as in 1992. Since there was no estimate of the internal loading rate for 1989, this rate was crudely estimated as the ratio of the concentration of total dissolved phosphorus (TDP) in the euphotic zone divided by TDP concentration in 1992, times the internal loading rate used in the 1992 calibration. Results of this run did not agree with the observed data for 1989.

Table 1. Calibration runs. Results from Bathtub 5.3 model calibrated and run using 1992 Pine Lake data and then run with 1989 flow, precipitation and different estimates of internal and external P loadings, to verify calibration. Chlorophyll *a* and Secchi depth predicted using both Bathtub 5.3 and equations developed from Pine Lake data and applied to Bathtub 5.3 observed and predicted total phosphorus concentration. Values reported are observed and estimated euphotic zone mean concentration, area-weighted by Bathtub 5.3 for the entire lake.

Run	Model Output	P Loadings	TP[c]	Model, Chl *a*[c]	Pine L Eqn, Chl *a*[c]	Model Secchi m.	Pine L. Eqn., Secchi	Key Findings
1	Observed (1992)		82	47.7	47.7	1.4	1.4	very close simulation
1	Estimated	1992 stream FWTP[a] $[P]_{int92}$[b]=measured rates	82.1	47.8	46.6	1.8	1.2	
2	Observed (1989)		46.7	16	16	2.4	2.4	unacceptable simulation (P over-estimated by Bathtub)
2	Estimated	1989 stream FWTP $[P]_{int89}=[TDP]_{89}/[TDP]_{92}*[P]_{int92}$	108.2	63.9	107	1.4	1.1	
3	Observed (1989)		46.7	16	16	2.4	2.4	improved simulation, but loading rates may not be realistic
3	Estimated	1992 stream FWTP $[P]_{int89}=0.25*[P]_{int92}$	53.8	31	19.4	2.8	1.5	

[a] FWTP = flow-weighted concentration of total phosphorus
[b] $[P]_{int}$ = phosphorus internal loading rate
[c] µg/L

The poor agreement between observed and predicted data in Run 2 could be due to a high internal loading rate and infrequent sampling and flow measurement in 1989 (n=7), compared to 1992 (n=18 for lake chemistry; daily flow estimates). A much improved verification (Run 3, Table 1), was prepared by using the flow-weighted concentration for each stream from 1992, with 1989 flow rates, and arbitrarily decreasing the internal loading rate to about one quarter of the 1992 rate. However, it is not known if the internal and external loading rates used for Run 3 are close to the rates that actually occurred in 1989. Considering the difference in the quality of observed data between 1989 and 1992, the 1992 calibration was deemed adequate for evaluation of reduced internal and external loadings.

2.3 PHOSPHORUS, CHLOROPHYLL *a* AND SECCHI DEPTH PREDICTIONS

During model verification it was determined that both the chlorophyll *a* and Secchi depth models in Bathtub 5.3 that performed best during calibration tended to over-estimate these variables at lower phosphorus levels, typical of measured data from 1989. For example in Run 3, the predicted total phosphorus was 15% higher than the observed data, while the model prediction for chlorophyll *a* was 94% higher than the observed data. Similarly, the model predicted transparency (Secchi depth) that was 33% higher than the observed 1989 data in Run 3, although both phosphorus and chlorophyll *a* were higher than the observed data. The chlorophyll *a* and Secchi depth models in Bathtub 5.3 are based on equations developed for reservoirs in the United States, against which this model was tested. These relationships may not be accurate for predictions at Pine Lake.

A chlorophyll *a*-total phosphorus regression equation was developed using euphotic zone data for Pine Lake and applied to the phosphorus predictions from each model run. Pine Lake data covering a broad range of phosphorus and chlorophyll *a* concentration, from three years (1984, 1989, 1992) were used to develop the equation. The 13 linear and non-linear regression models available in the water quality statistics package WQHYDRO (Aroner 1994) were evaluated, and those that were statistically significant were refined using a robust regression procedure, which minimizes the effects of data with a large residual. The models with the best correlation coefficients and lowest standard errors were then compared to measured data, and the model which best matched the observed data (log-quadratic model in Figure 2) was selected. Similarly, a Secchi depth-

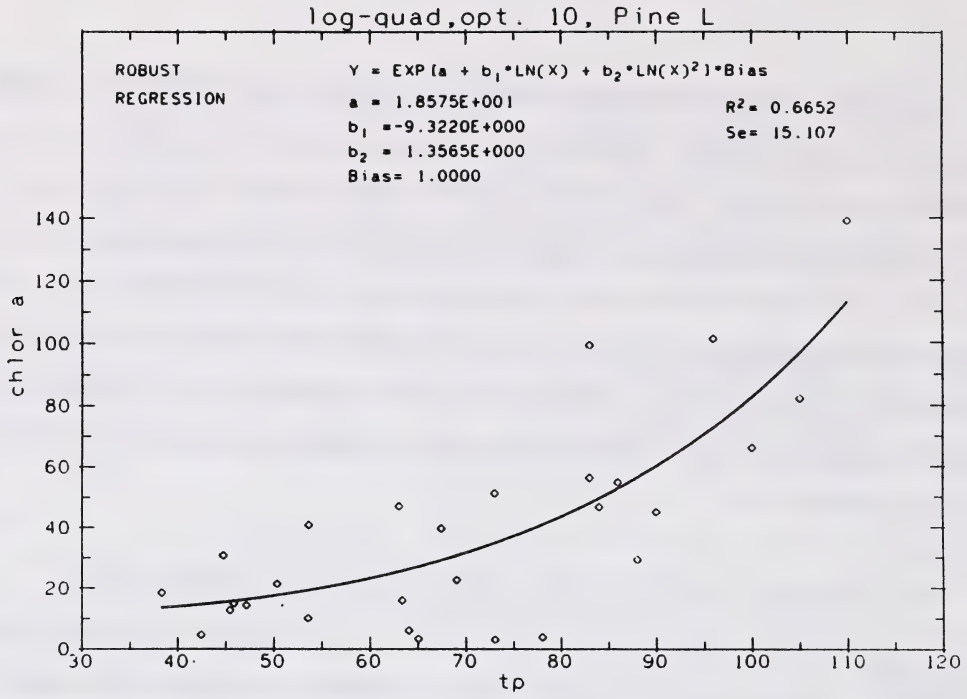

Figure 2. Relationship between total phosphorus and chlorophyll *a* in Pine Lake (1984, 1989, 1992). Units are μg/L

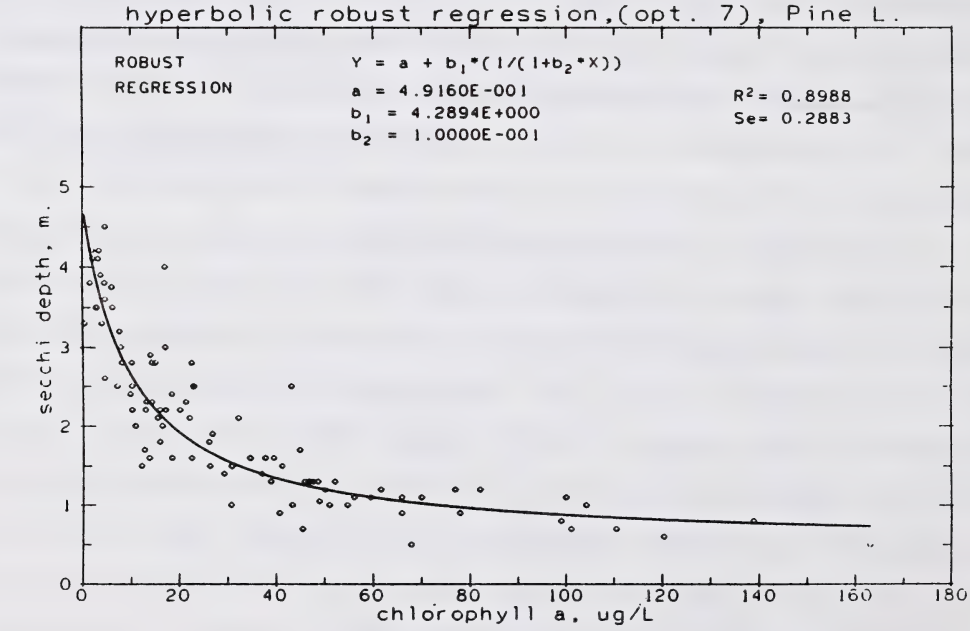

Figure 3. Relationship between Secchi depth and chlorophyll *a* in Pine Lake (1984-92).

chlorophyll *a* regression equation (hyperbolic model in Figure 3) was developed using the same 1984-92 Pine Lake data, and used to estimate mean Secchi depth from the chlorophyll *a* predictions.

2.4 SCENARIOS EVALUATED DURING PRODUCTION RUNS

The following four scenarios, covering a wide range of possible reductions in internal and external loading, were evaluated:

Run 4. Streams 1,3,4,5 and 6 annual flow-weighted total phosphorus concentrations (FWTP's) (and orthophosphorus) reduced to the 1992 concentrations for stream 7 (0.132 mg/L FWTP), based on the assumption that stream 7 represents the lowest phosphorus level that can be achieved in the Pine Lake basin. Streams 2 and 7 FWTP's remained unchanged in all production runs, as these were reference (control) streams, without mitigation work. The internal loading rate was reduced by an arbitrary 25% from the 1992 loading rate. The 25% reduction was based on the phosphorus export rate calculated for the proposed hypolimnetic withdrawal system (as designed in plans dated January 26, 1996) during a wet year similar to 1994. Diffuse phosphorus loading was at the rates used in the 1992 calibration.

Run 5. Streams 1,3,4,5 and 6 FWTP's reduced to the 1992 FWTP for stream 7. The internal loading rate was reduced by an arbitrary 50% from the 1992 loading rate. Diffuse phosphorus loading was at the rates used in the 1992 calibration.

Run 6. Streams 1,3,4,5 and 6 FWTP's reduced to the 1992 FWTP for stream 7. The internal loading rate was reduced to 35% of the 1992 rate over a 10 year period to the year 2006. This reduction assumes that, based on the export rate calculations, the mass of phosphorus in Pine Lake sediments and the release rate will be reduced by 25% during a wet year like 1994 (observed frequency of high lake level: 2/10), by 14.2% during a year with levels similar to 1993 (2/10), by 8.7% during relatively dry years like 1992 (3/10), and will not be reduced in three years of 10 when levels are too low for system operation. Diffuse phosphorus loading was reduced to the 1992 FWTP for stream 7.

Run 7. Streams 1,3,4,5 and 6 FWTP's reduced to 0.5 of the 1992 FWTP for stream 7, to determine the sensitivity of the model to further reductions in stream phosphorus loading. This large a reduction in stream loading would be very difficult to achieve, given the level of development in the

watershed. The internal loading rate was reduced to 35% of the 1992 rate over a 10 year period. Diffuse phosphorus loading was reduced to the 1992 FWTP for stream 7.

3.0 RESULTS AND DISCUSSION

Results of the model runs with reduced external and internal phosphorus loadings are summarized in Table 2 and Figure 4. In each of the production runs, the model predicts that Pine Lake would remain a moderately productive lake, but should respond to the restoration program with a large reduction in algal biomass (decrease from current biomass by 55 to 73%) and a large increase in transparency (increase in Secchi depth from 36 to 71%). Even with a relatively modest 25% decrease in the internal loading rate (Run 4), the model predicts a change in algal biomass and transparency that would be readily apparent to lake users. With greatly reduced internal and external loadings, chlorophyll *a* and transparency would be reduced to the lower range of eutrophic conditions (Runs 6 and 7), and phosphorus would decline to the upper mesotrophic range (Run 7).

It is not possible to accurately predict the degree to which external and internal phosphorus loading rates will respond to the current watershed and in-lake treatments. Welch and Cooke (1995) reviewed results from various lake restoration projects without in-lake treatment, and concluded that internal phosphorus loading will eventually decline following a reduction in external loading, but they note that internal loading may temporarily increase and the decline may occur over a long period of time. They reported that internal loading was only reduced quickly in one lake to which external loading was reduced, without additional in-lake treatment, and this lake had a relatively high Osgood index (mean depth/square root of surface area) of 7.3. They note this indicates that a large volume of the lake is involved in mixing. By comparison, Pine Lake has an Osgood index of 2.6, which suggests that a reduction in internal loading will require effective in-lake treatment.

A realistic objective for the Pine Lake Restoration Program would be to achieve the conditions modelled in Run 6, which would reduce algal productivity to the borderline between mesotrophic and eutrophic. As described above, the assumptions for this scenario include a reasonable estimate of the decrease in internal phosphorus loading that can be achieved over 10 years, and assumes that phosphorus levels in the critical streams and diffuse runoff can be only

Table 2. Production runs. Results of Bathtub 5.3 model runs with 1992 flow and precipitation and reduced estimates of internal and external P loadings. Chlorophyll *a* was predicted using a regression equation developed from Pine Lake data, and applied to total phosphorus concentrations predicted using Bathtub 5.3. Secchi depth was then predicted from these chlorophyll *a* estimates using another equation developed from Pine Lake data. Values reported are observed and estimated euphotic zone mean concentration, area-weighted by Bathtub 5.3 for the entire lake.

Run	Model Output	P Loadings	TP[c]	Chl *a*[c]	Secchi, m	Key Findings
4	Observed (1992)		82.0 (eutro)[d]	47.7 (hyper)[d]	1.4 (hyper)[d]	- 55% reduction in algal biomass - 36% increase in transparency
4	Estimated (Future)	1992 FWTP #7 diffuse runoff as in 1992 $[P]_{int}=0.75*[P]_{int\ 92}$	57.2 (eutro)	21.4 (eutro)	1.9 (eutro)	
5	Observed (1992)		82.0 (eutro)	47.7 (hyper)	1.4 (hyper)	- 67% reduction in algal biomass - 57% increase in transparency
5	Estimated (Future)	1992 FWTP #7 diffuse runoff as in 1992 $[P]_{int}=0.5*[P]_{int\ 92}$	45.1 (eutro)	15.6 (eutro)	2.2 (eutro)	
6	Observed (1992)		82.0 (eutro)	47.7 (hyper)	1.4 (hyper)	- 72% reduction in algal biomass - 64% increase in transparency
6	Estimated (2006)	1992 FWTP #7 diffuse runoff at FWTP #7 $[P]_{int}=0.35*[P]_{int\ 92}$	36.3 (eutro)	13.4 (eutro)	2.3 (eutro)	
7	Observed (1992)		82.0 (eutro)	47.7 (hyper)	1.4 (hyper)	- 73% reduction in algal biomass - 71% increase in transparency
7	Estimated (2006)	0.5*1992 FWTP #7 diffuse runoff at FWTP #7 $[P]_{int}=0.35*[P]_{int\ 92}$	31.3 (meso)[d]	12.9 (eutro)	2.4 (eutro)	

[a] FWTP = flow-weighted concentration of total phosphorus
[b] $[P]_{int}$ = phosphorus internal loading rate
[c] µg/L
[d] OECD fixed boundary system trophic categories: (1) meso = mesotrophic, a moderate level of algal productivity; (2) eutro = eutrophic, a high level of algal productivity; (3) hyper = hypertrophic, extreme levels of algal productivity, with frequent algal blooms

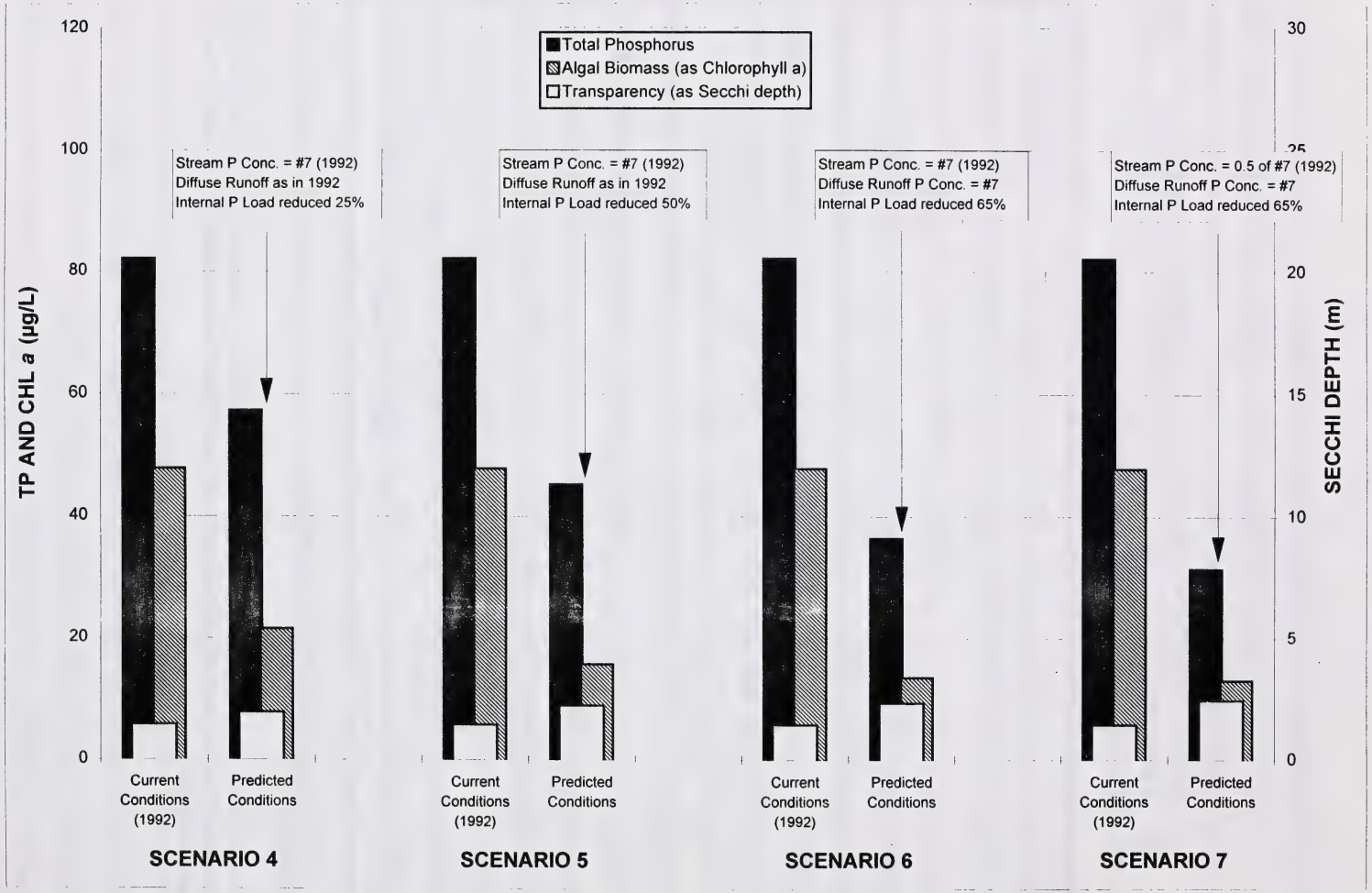

Figure 4. Predicted phosphorus and chlorophyll *a* concentrations and Secchi depths for four modelling scenarios.

improved to levels currently occurring in the least impacted stream in the Pine Lake basin (Stream 7).

The results of Run 7 suggest that very large reductions in stream loading (to 0.5 of the FWTP for stream 7), from the loadings modelled in Run 6, would only result in modest further decreases in algal productivity to the borderline zone between mesotrophic and eutrophic. A decrease in algal productivity to the mesotrophic level would achieve the stated objective of the Pine Lake Restoration Society of reducing algal productivity to levels that occurred prior to European settlement. Deep core analysis of diatom species composition at the University of Alberta suggests that Pine Lake was in the mesotrophic range of productivity before European settlement (S. Blakney. 1996; personal communication).

A further reduction in algal productivity to the middle of the mesotrophic range would be very difficult to achieve considering the level of development in the watershed and history of the lake. Greatly reduced algal productivity may also have negative impacts on other uses of Pine Lake. For example, fish productivity in lakes is generally correlated with levels of chlorophyll *a* (Downing *et al.* 1990). Therefore, reduced fish production in Pine Lake could be anticipated if algal productivity is greatly reduced.

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